Socio-technical transitions in UK electricity: part 2 - technologies and sustainability

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Socio-technical Transitions in UK Electricity: Part 2 – Technologies and Sustainability†

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ABSTRACT

A large interdisciplinary consortium of engineers, social scientists and policy analysts have developed three low carbon, more electric transition pathways for the United Kingdom (UK): described as '*Market Rules*' (MR), '*Central Co-ordination*' (CC) and '*Thousand Flowers*' (TF) respectively. It adapts an approach based on earlier work on understanding transitions, using a multi-level perspective with landscape, regime and niche levels, and its application to the development of 'socio-technical scenarios'. These pathways to 2050 focus on the power sector, including the potential for increasing use of low carbon electricity for heating and transport, within the context of critical *European Union* developments and policies. Part 1 describes studies of historical energy and infrastructure transitions were described that help the understanding of the dynamics and timing of past transitions. The role of large-scale and smallscale 'actors' in the electricity sector and the methods used to develop the pathways were then described. In Part 2, associated technologies are evaluated in order to determine the choices that need to be made by UK energy policymakers and stakeholders. Finally, all three pathways have been appraised in terms of their environmental performance using complementary lifecycle assessment and footprinting methods. Lessons can clearly be drawn for other industrialised nations attempting to decarbonise their electricity generation systems, although local circumstances will determine the country- and region-specific options.

Keywords: Energy; Climate change; Business

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1. Introduction

1.1 Background

Electricity generation presently contributes approximately 30% of United Kingdom (UK) carbon dioxide (CO_2) emissions (Hammond, 2000; POST, 2007) the principal 'greenhouse gas' (GHG) having an atmospheric residence time of about 100 years (Hammond, 2000, IPCC, 2013). This share mainly arises from the use of fossil fuelled (coal and natural gas) power stations. Changes in atmospheric concentrations of GHGs affect the energy balance of the global climate system. Human activities have led to quite dramatic increases since 1950 in the 'basket' of GHGs incorporated in the Kyoto Protocol; concentrations have risen from 330 ppm in 1975 (IPCC, 2013) to about 408 ppm in 2018 (WMO, 2019). The recent (2013) scientific assessment by the *Intergovernmental Panel on Climate Change* (IPCC) asserts that it is 'extremely likely' that humans are the dominant influence on the observed global warming since the mid-20th Century (IPCC, 2013). The British Government therefore introduced a bold, legally binding target of reducing the nation's CO_2 emissions overall by 80% by 2050 in comparison to a 1990 baseline (Hammond and Pearson, 2013) in their 2008 *Climate Change Act*. Achieving this carbon reduction target will require a challenging transition in Britain's systems for producing, delivering and using energy that is not only low carbon, but also secure and affordable; thus resolving the so-called energy policy '*trilemma*' (Hammond & Pearson, 2017). The 2015 *Paris Agreement* following the COP21 meeting in that city aims to keep temperatures "well below 2°C above pre-industrial levels and to pursue efforts to limit the temperature increase to 1.5°C above pre-industrial levels" (Ares & Hirst, 2015). The 2°C figure is broadly consistent with the 2050 UK CO_2 emissions target. However, *bottom-up* pledges received by countries prior to the Paris Conference [the so-called '*Intended Nationally Determined Contributions*' (INDCs)] for national GHG mitigation efforts are expected by analysts of the *United Nations Framework Convention on Climate Change* (UNFCCC) (Ares & Hirst, 2015) to result in a warming of around 2.7°C. So the world still faces a significant challenge of reducing GHG emissions further in order to bring global warming into line with the aspirations in the *Paris Agreement*. Indeed, the IPCC in their recent 'special report' on the implications of keeping temperatures down to 1.5°C (IPCC, 2019) argued that humanity has just 12 years to respond to the climate change challenge (i.e., by about 2030 rather than 2050 presently incorporated in international agreements), if it wishes to keep global warming to 1.5°C above pre-industrial levels. Thus, it needs to instigate appropriate actions in the very near future. The British *Climate Change Act* was subsequently amended by the UK Government in June 2019 in order to target a reduction of all GHG emissions to net zero by 2050.

The history of electricity generation since the time of Edison has been based around the concept of employing large, centralised power stations **(**Hughes, 1983; Buchanan, 1994; Hammond and Waldron, 2008). Consequently, some 62% of electricity within Britain in 2018, the most recent full year data available at the time of writing in the annual *Digest of United Kingdom Energy Statistics* [DUKES] (BEIS, 2019), is still generated by large thermal power plants [from coal

(5%), natural gas (39%), and nuclear power (18%)]. These are connected to a high-voltage transmission grid, and is then distributed to end-users via regional low-voltage distribution networks (Hammond, 2000; POST, 2007). This centralised model has delivered economies of scale and reliability (Hammond, 2000), but there are significant drawbacks. The UK *Electricity Supply Industry* (ESI), for example, currently has a heavy reliance on primary fuels, particularly coal and natural gas (BEIS, 2019). Much of the electricity grid was constructed in the 1950s and 1960s. It is therefore heavily reinforced in former coal-mining areas, and is nearing the end of its design life (Hammond, 2000; POST, 2007; Hammond and Pearson, 2013). Power flow is restricted from Scotland to England (2.2GW$_e$), and via the interconnectors (in the form of highvoltage undersea cables) to France, Northern Ireland and the Netherlands (Hammond, 2000; Hammond and Pearson, 2013). The grid will require not only renewal, but also reconfiguration in order to accommodate a greater proportion of distributed generation.

1.2 The Issues Considered

A large interdisciplinary consortium of engineers, social scientists and policy analysts have developed three low carbon transition pathways for a more electric future in the UK out to 2050: termed '*Market Rules*' (MR), '*Central Co-ordination*' (CC) and '*Thousand Flowers*' (TF) respectively. This large consortium of nine university partners was originally funded via the strategic partnership between *e.on UK* (the electricity generator) and the UK *Engineering and Physical Sciences Research Council* (EPSRC) to study the role of electricity within the context of '*Transition Pathways to a Low Carbon Economy*' (2008-2012), and then renewed with funding solely from the EPSRC under the title *'Realising Transition Pathways: Whole Systems Analysis for a UK More Electric Low Carbon Energy Future*' (RTP) (2012-2016).] The present research examined the most recent *version 2.1* (v2.1) of the pathway narratives (Foxon *et al.*, 2010; Hammond and Pearson, 2017; Chilvers *et al.*, 2017): driven by the market, central government intervention, and civil society (e.g., local communities and nongovernmental organisations [NGOs]) initiatives. This emphasis on 'governance' as a prime mover of market development is a novel feature in terms of energy futures research in Britain (Foxon *et al.*, 2010; Hammond and Pearson, 2013; Chilvers *et al.*, 2017). This transition pathways research has focused on the choices and actions needed to *get there from here*, and on the analysis of the pathways' technical, socio-economic and environmental implications. It built on an approach based on earlier work on understanding transitions, which is fully described in a companion paper (Part 1). The current 'socio-technical scenarios' or transition pathways focus on power generation, including the potential for increasing use of low-carbon electricity for heating and transport. The extent to which choices need to be made by UK energy policymakers and stakeholders between the large-scale and small-scale *actors*, pathways and associated technologies are discussed.

The present research programme sought to understand and contribute to potential future transitions of UK energy systems and to enhance policy thinking and decision-making. In Part 1 studies of historical energy and infrastructure transitions - which inform how the broad, longterm sweep of change that arises out of interactions between *actors* or *actor networks*, institutions and infrastructures – are used to aid the understanding the dynamics and timing of transitions (Chilvers *et al.*, 2017; Pearson, 2018). The *multi-level perspective* (MLP) – encompassing, as noted there, *macro-landscape pressures*, *socio-technical regimes* and *niche innovations* - has been used as the basis for developing the socio-technical scenarios [as depicted in Part 1 Fig. 2 (Foxon *et al.*, 2010)]. These can be employed to explore the potential future development of socio-technical systems through interactions between ongoing processes at the three levels (Foxon, 2013; Hammond and Pearson, 2013; Hammond and Pearson, 2017).

In the current paper (Part 2) *horizon scanning* and *energy technology assessments* (ETAs) of the energy technologies that influence the three UK *transition pathways* are employed to provide an understanding the future interplay of the energy policy *trilemma*, i.e., achieving deep GHG emission cuts, whilst maintaining a secure and affordable energy system, and addressing how resulting tensions might be resolved. Indicative ETAs are used to identify the components of a *balance sheet* of technological credits and debits to evaluate their societal impacts, and to determine whether they will enhance Britain's move towards a low carbon dioxide ('low-carbon') future in 2050 and beyond. Here (Part 2) all three pathways (MR, CC and TF) have also been evaluated in terms of their environmental performance using complementary *life cycle assessment* (LCA) and footprinting methods**.** The energy analysis and environmental LCAs reported by Hammond *et al*. (2013) and Hammond and O'Grady (2014; 2017a; 2017b), evaluated v1.1 and v2.1 of the pathways respectively). *Environmental footprint analysis* (EFA) has been employed to estimate the environmental and resource burdens associated with UK power generation based on historic data and the three transition pathways (Hammond *et al.*, 2019)**.**

2. Horizon Scanning and Technology Assessment

2.1 Scanning the Energy Technology Horizon

Developments are ongoing at the *niche* level (see again Part 1 Fig. 2) through the formation of technology-specific innovation systems around a number of different technological alternatives. Technological discoveries may encompass one or more technological/ market *niches* (Markard and Truffer, 2008). Alternatives include centralised options on a large-scale, such as offshore wind, wave and tidal power, tidal barrages, biomass co-firing, new nuclear power, and CCS. In contrast, as noted, there is presently a growth in interest in innovative decentralised options, including CHP (using gas-powered fuel cells or Stirling Engines), microwind turbines, solar photovoltaic arrays, solar thermal heating, and air-sourced and groundsource heat pumps, and local energy crops. A key task for the development of the UK *transition pathways* is the elucidation of potential 'virtuous cycles' between the different processes or functions which could occur within each of these energy innovation systems. They may be seen as competing for resources and recognition against each other within the centralised or decentralised paradigm, at the same time as these two archetypes compete against each other. Obviously, complementarities may also exist between different the technological alternatives, both within and between paradigms.

Technological choices in the UK power sector are likely to vary significantly out to 2050 (Chilvers *et al.*, 2017). For example, over the last few years the outlook for both coal-fired power stations with CCS and nuclear power has changed dramatically. The UK Government indicated (in November 2015) their wish to phase out unabated coal-fired power stations by 2025, and gave new gas-fired power stations priority. Likewise, the prospects of new nuclear build was hit by both concerns following the 2011 Fukushima Daiichi nuclear power plant disaster in Japan and a reassessment of the economics of nuclear power by some of the *big players*, such as the investment decision by the French utility *eDF Energy* in regard to the construction of the Hinkley Point C nuclear power plant (in rural Somerset, in South West England). Nevertheless, in 2013, the UK Government gave the go-ahead for a consortium of France's state-owned *eDF Energy* and Chinese investors (China National Nuclear Corporation and China General Nuclear Power Corporation) to build two new nuclear reactors of 3260 MW_e (planned) at the site with a 35-year price guarantee of £92.50 for every megawatt hour (MWh) generated. These short-term changes in attitudes to low carbon technologies mean that the technology choices implicit in each of the existing pathways need to be kept under continuous review (Chilvers *et al.*, 2017).

Horizon Scanning involves a portfolio of methods that enable energy researchers and other power sector stakeholders to increase their awareness of important emerging influences on the UK energy system and its environment. It provides a major strand in proactive risk management (Hammond and Waldron, 2008) and strategic thinking as the UK energy sector moves forward. Parker *et al*. (2014), for example, used a modified Delphi technique for horizon scanning in order to identify some thirty emergent policy issues which strongly featured science and technology, and which would necessitate public engagement as the policies were being developed. This exercise? was driven, in part, by concerns over the use of hydraulic fracturing (or 'fracking') by fossil fuel companies for UK shale gas resources in the UK. A disparate group of people with interests over the science and policy interface (e.g., policy makers and advisers, academics, and the private sector) initially elicited a long list of issues (Parker *et al*., 2014). These were then refined into a shorter list that were viewed as being of top priority for policy makers. They included challenges related to energy and environment, such as policies concerning interdisciplinary *whole energy systems* science [incorporated by a partner in the RTP Consortium: Dr Jason Chilvers (Parker *et al*., 2014)]. A variety of alternative techniques are available for use in identifying emerging issues in the UK energy sector (Chilvers *et al.*, 2017). *Arup Foresight* (part of the independent firm of designers, planners, engineers, and consultants) have, for example, employed STEEP (*Social, Technological, Economic, Environmental, Political*) analysis to examine drivers for change in both the energy and climate change fields. Horizon scanning has enabled the RTP Consortium partners to take a more critical look at the 'mega trends' and uncertainties (both in the UK and internationally) implicit in our three transition pathways devised via stakeholder engagement, along with the associated technologies. Similar activities have been undertaken by the *Energy Research Partnership* (ERP) to evaluate recent changes to the energy market broadly, such as the price of oil, which have impacted on alternative scenarios devised by their partner, the *UK Energy Research Centre* (UKERC).

2.2 'Whole Systems' Evaluation of Energy Technologies and Systems

2.2.1 Methods and Applications

The RTP Consortium have used a similar approach to STEEP, in conjunction with more formal methods of *Technology Assessment* (see, for example, Vig.and Paschen, 2000; Tran and Daim, 2008), to evaluate a number of the main disruptive energy technologies. These studies have sought to identify the components of a *balance sheet* of technological credits and debits in order to evaluate their societal impacts, and to determine whether they are compatible with Britain's move towards a low carbon future in 2050 and beyond. Indicative *energy technology assessments* (ETAs) have therefore been carried out for a variety of energy technologies, e.g., UK shale gas extraction (Hammond and O'Grady, 2014), carbon capture and storage (CCS) (Hammond, 2013; Hammond and Spargo, 2014), advanced rechargeable batteries (Hammond and Hazeldine, 2015), *Rare Earth Elements* (REE) as a constraint on *clean* energy technologies (Hammond and Mitchell, 2014), nuclear power plants (Hammond, 2011), and tidal power barrages (Hammond *et al.*, 2018). These ETAs were all indicative in the sense of being a simplified evaluation and illustration of the performance of state-of-the-art devices. Nevertheless, such assessments provide a valuable evidence base for developers, policy makers, and other stakeholders. Each technology was evaluated using a combination of quantitative and qualitative methods within the spirit of the STEEP approach.

2.2.2 Shale Gas Extraction

The most controversial of these studies was arguably that concerning the benefits and 'costs' of *shale gas fracking* in Britain (Hammond and O'Grady, 2014; Parker *et al*., 2014). Exploratory drilling in the UK is at an early stage, with great uncertainty over the scale of the potential shale gas resource (Hammond and O'Grady, 2014; Whitelaw *et al*., 2019). However, such activities are already meeting fierce community resistance. Like all energy technologies it exhibits unwanted side-effects that simply differ in their level of severity compared to other options. Successful extraction might contribute positively in terms of fuel security and independence, as well as jobs and growth (Hammond and O'Grady, 2014). Shale gas may also make a contribution to attaining the UK's statutory GHG emissions targets, although potentially harmful environmental impacts need to be satisfactorily resolved via appropriate monitoring and robust regulation. It is unlikely that gas bills for UK household and industrial consumers would fall dramatically as they have done in North America, because Britain is linked to the wider European gas market. Anything produced in the UK would be a 'drop in the ocean' compared to imports via either pipelines or *liquefied natural gas* (LNG) tankers. Finally, the socio-economic advantages and disadvantages of shale gas fracking are not evenly distributed between various communities and demographic groups (Hammond and O'Grady, 2014). Community engagement in a genuinely participative process – where the government is prepared to change course in response to the evidence and public opinion - will consequently be critically important for the adoption of any new energy option.

2.2.3 Carbon Capture & Storage

CCS facilities coupled to fossil fuelled power plants or industrial sites provide a key climate change mitigation strategy that potentially permits the continued use of fossil fuel resources, whilst reducing the CO_2 emissions. Hammond and Spargo (2014) highlight the potential design routes for the capture, transport, clustering, and storage of CO_2 from UK power plants. Due to lower operating efficiencies, the CCS plants showed a longer *energy payback period* and a lower *energy gain ratio* than conventional plant. The *Transition Pathways* team (Hammond *et al*., 2013; Hammond and O'Grady (2014) found that, when upstream effects are taken into account, this can reduce the capture rate to 70% (compared to the anticipated design figure of around 90%) over the life-cycle. There are also several technical and financial obstacles that need to be overcome (Hammond, 2013; Chilvers *et al.*, 2017), including the adoption of an appropriate legislative framework and the need for full CCS chain risk assessments. There are uncertainties over the full-scale power plant CCS technical performance and costs, which may only become clearer when the first demonstrators are operational. The UK Government established a *CCS Cost Reduction Task Force* (Hammond, 2013) as an industry-led joint venture to assist with the challenge of making CCS a commercially viable operation by the early 2020s. The main cost reduction opportunities were seen as being (Hammond, 2013; Chilvers *et al.*, 2017): (i) transport and storage scale and utilisation, (ii) improved financeability for the CCS chain, and finally (iii) improved engineering designs and performance. Greater financial incentives for carbon abatement could, in principal, be secured through a higher carbon price from the European Union *Emissions Trading Scheme* (EU ETS), although that has been a significant disappointment in terms of the carbon price level. The UK Government is currently working with industry to support the development of a cost-competitive CCS industry in the 2020s. Through its 2017 *Clean Growth Strategy* (CGS) it intends to invest £162 million in a clean growth innovation funding out to 2021 (Cooper and Hammond, 2018) - much of it earmarked for CCS - to support R&D and innovation, although only a few small-scale CO_2 capture demonstrations have so far been implemented. The Government recently stated that, "We are committed to the UK having the option to deploy CCUS at scale during the 2030s subject to the costs coming down sufficiently", noting that this commitment "is contingent on industry joining us in meeting the challenge of delivery" (HM Government, 2018).

2.2.4 Nuclear Power

The lives of existing nuclear plant have typically been extended to around 40 years [e.g., Hunterston B was financed for 25 years with an expectation of 35 years, and subsequently extended by 7 years (Chilvers *et al.*, 2017)]. Nevertheless Britain, as with other nuclearpowered European countries, is progressively decommissioning its older nuclear power stations during the next decade or so. This will leave only the Sizewell B *Pressurised Water Reactor* (PWR) station in the UK, with nuclear power holding a considerably reduced share of electricity generation. Consequently, a new generation of nuclear power stations may need to be part of the power generation mix in order to decarbonise the electricity sector by around 2030-2050 (Hammond, 2011; Chilvers *et al.*, 2017). A number of issues affecting the use of nuclear electricity generation in Western Europe were considered as part of an indicative ETA

(Hammond, 2011), including its cost, industrial strategy needs, and the public acceptability of nuclear power. The contribution of nuclear power stations to achieving CO_2 targets aimed at relieving global warming has been examined in the context of alternative strategies for sustainable development, including renewable energy sources and energy-efficiency measures. Successive British governments have advocated a key role for nuclear power in the future UK energy mix, alongside other low carbon technologies. They seek to encourage energy utility companies to invest in new nuclear build (DECC, 2011). Nuclear power is an energy technology with near-zero CO_2 emissions that is available now on a large-scale. It could therefore play a useful role as part of a low carbon energy strategy. Nevertheless, energy efficiency measures currently displace between 2.5 and 20 times more carbon dioxide than would new nuclear power plant per dollar (euro or pound) invested (Keeping, 1990). Indeed the former UK *Sustainable Development Commission* (SDC, 2006) argued that a new nuclear programme would give out the wrong signal to both consumers and businesses. It would not justify public subsidy and, if implemented on a significant scale, might hold out a risk that the taxpayer will be have "to pick up the tab" (SDC, 2006), although this would be mitigated as all new build nuclear projects are required to have agreed funded decommissioning plans. In addition, the adoption of either short- or medium-term reactor plant technologies would obviously be critically dependent on public attitudes to nuclear power in Britain and elsewhere (Hammond, 2000; Hammond and Waldron, 2008; Hammond, 2011), particularly in regard to safety, waste management and nuclear proliferation. Nuclear power gives rise to ongoing problems with high and intermediate-level waste disposal (Hammond, 2011), although a deep underground repository is the preferred option. The siting of such a facility has yet to be resolved in the UK. These consequently remain significant barriers to a large scale-up of nuclear power in Britain, but the waste disposal issue will need to be resolved due to legacy radioactive wastes regardless of extent of any new nuclear build. However, the construction of the first new nuclear power in the UK for over 20 years began in 2016, following the signing of contracts between the UK Government, *EDF* and *China General Nuclear* (CGN) for the 'Hinkley Point C' (HPC) nuclear power station, which is predicted to take 10 years to build (Barton *et al*., 2018).

2.2.5 Tidal Power Barrages

The Severn Estuary, which empties into the Bristol Channel, is seen as one of the premium international tidal power locations because it has the second largest tidal range in the world (15 m). It would involve the construction of a 10 mile long *barrage* (dam) between Lavernock Point (south of Cardiff, Wales), and Brean Down on the Somerset coast, England The use of technology that utilises the tidal range is well-established, and typically has an estimated lifetime of 120 years (Barton *et al*., 2018; Hammond *et al*., 2018). Both the Cardiff-Weston and the smaller Shoots barrages on the River Severn have been evaluated by Hammond *et al.* (2018) using various ETA techniques to determine their net energy output, carbon footprint and financial investment criteria, alongside various critical technical and environmental issues. These tidal power schemes were assessed over their foreseen lifespan of 120 years in terms of its cradle-to-site, operation and maintenance requirements. The proposed Cardiff-Weston Barrage would yield relatively attractive figures of merit in terms of its net energy and carbon emissions, although its financial performance is poorer than alternative power generators. Comparisons were made with the much smaller, Shoots Barrage scheme that would be located up-river of the Severn road crossings, and which is favoured by environmental groups, because of its more benign ecological and environmental impacts (Hammond *et al*., 2018). The capital costs would be recouped, but only with very long pay-back periods. Thus, the UK Government decided that a proposed 8.64 GW Cardiff-Weston barrage was not required to meet 2020 renewable energy targets (Hammond *et al*., 2018), due to these cost considerations, as well as the local environmental impacts. They argued that it should not be supported by public funds, although the project may still be considered in the future (DECC, 2011). However, plans for a 320 MW tidal lagoon 'pathfinder' power plant in Swansea Bay were supported by a government-commissioned review (Barton *et al*., 2018; Hammond *et al*., 2018), but it was ultimately rejected for public funding in 2018. The pioneering scheme is presently being 'rebooted' by private sector investors, who believe they can build it without the help of government.

2.2.6 Other Green Technologies

The suitability of *advanced rechargeable battery technologies* (ARBT) for different applications, such as electric vehicles (EV), consumer electronics, load levelling, and stationary power storage, has been the subject of another ETA (Hammond and Hazeldine, 2015). These energy storage devices were compared to more mature Nickel-Cadmium (Ni-Cd) batteries in order to gain a sense of perspective regarding the performance of the ARBT. Li-ion batteries (LIB) currently dominate the rechargeable battery market and are likely to continue to do so in the short-term in view of their excellent all-round performance (Hammond and Hazeldine, 2015), and firm grip on consumer electronics. The high charge/discharge cycle life of these LIBs mean that their use may grow in the electric vehicle (EV) sector, and to a lesser extent in load levelling, if safety concerns are overcome and costs fall significantly. However, in view of the competition from *Lithium-ion polymer* (LIP) batteries their long-term future is uncertain. LIP batteries exhibited attractive values of gravimetric energy density, volumetric energy density, and power density (Hammond and Hazeldine, 2015). Although, if safety concerns with LIB are overcome and costs fall significantly, there may be growth in the EV sector and to a lesser extent load-levelling, where LIB can exploit their relatively high cycle life.

Rare earth batteries and magnets are key elements of hybrid vehicles and gearless wind turbines, and phosphors are critical in energy saving lighting. Hammond and Mitchell (2014) argued that *rare earth elements* (REE) may place a significant constraint on the development of some low carbon (or *clean*) energy technologies. These materials are not actually rare in terms of their abundance, but the number and location of mines are restricted due, in part, to economic considerations. Current REE reserves stand at about 110 million tonnes with around half in the People's Republic of China (PRC), although other countries like the USA, Commonwealth of Independent States (CIS) [the former Soviet Republics], and Australia hold substantial reserves. However, production in China dominates the market, with ~97% of the global total, and this will remain so until new mines are developed. The PRC has in the recent past limited its export of REE in order to give preference to the export of manufactured products. It is likely that supply constraints will become less critical in the medium to longterm as more mines come into operation, and thus further reserves become available (Hammond and Mitchell, 2014). Such constraints could be eased by reducing the amount of material required per application, or changing the technology altogether. Lithium-ion batteries, for example, are already a viable replacement for nickel-metal-hydride units in hybrid vehicles.

LIB costs have fallen from $1,000/kWh to <$250/kWh for a battery pack in less than 8 years (Shojaei, 2017). REE are not currently recycled, either pre or post-use. There are processes available that could be utilised for this purpose (Hammond and Mitchell, 2014), although they don't currently appear to be economically viable options.

2.2.7 Cross-technology Comparisons of Performance Criteria

An evaluation of the *energy densities* and *spatial footprints* of both conventional and renewable generators was undertaken by Cheng and Hammond (2017) on a life-cycle (or 'cradle-to-gate') basis. It had previously been argued in the literature that some of the renewable power generators take up far more land than their fossil fuelled or nuclear-powered counterparts. This assertion has consequentially been tested over the 'full fuel chain' in order to provide a valuable evidence base for developers, policy makers, and other stakeholders. The energy densities over this domain were determined using 'process energy analysis', whereby the energy required to produce electricity is evaluated taking into account both the direct energy use and the indirect (or 'embodied') energy requirements for materials and capital outputs. Here the resulting *energy densities* (GWh/km^2) are presented in Fig. 1, and those for the corresponding *spatial footprints* (km^2/TWh) in Fig. 2 (Cheng and Hammond, 2017). It can be seen that the nuclear fuel cycle (both with diffusion and centrifuge enrichment) was found to have the highest energy density of the technologies evaluated, with bioenergy plants having the lowest. Onshore wind power exhibited a relatively promising energy density; being greater than that for its offshore counterpart. The energy density of the latter fell below that of solar PV arrays. Thus, renewables were found to produce *dilute electricity* overall with a spatial footprint that is orders-of-magnitude higher than for conventional sources. Clearly, there are many other sustainability criteria that will determine their usefulness in the transition towards a low carbon future (Cheng and Hammond, 2017; Chilvers *et al.*, 2017).

3. Environmental Appraisal of the UK Transition Pathways

3.1 Environmental Life Cycle Assessment (LCA)

The energy and environmental appraisal of the three *transition pathways* and associated power technologies have been evaluated on a life-cycle basis (Hammond and O'Grady, 2014; 2017a; 2017b). This process employed a toolkit of techniques to explore and evaluate the *whole systems* consequences of the selected transition pathways, such as the (embodied and process) energy and carbon implications of the pathways and technology mixes, and their environmental burdens [as indicated by environmental *life-cycle assessment* (LCA)]. A comprehensive review of the LCA of energy systems by Hammond *et al.* (2015) included an overview of the historic development of LCA from the early 1990s, and its subsequent codification by the *International Standards Organization* (ISO). Environmental appraisal of energy systems needs to be conducted on a life-cycle basis, i.e., embracing the full range of extraction, production, distribution, and end-of-life processes or technologies (Baumann and Tillman, 2004; Curran, 2012; Hammond *et al.*, 2013; Hammond and O'Grady, 2014; Hammond *et al.*, 2015). In a full or detailed LCA the energy and materials used and pollutants or wastes released into the environment as a consequence of an activity or service are quantified over the whole life-cycle; typically from cradle-to-gate (Hammond *et al.*, 2015). Such studies are often geographically diverse; that is, the energy and material inputs associated with the activity may be drawn from any continent or geo-political region of the world. They involve four main LCA stages that follow a logical sequence of *goal definition and scoping*, *inventory analysis*, *impact assessment*, and *interpretation* of the results.

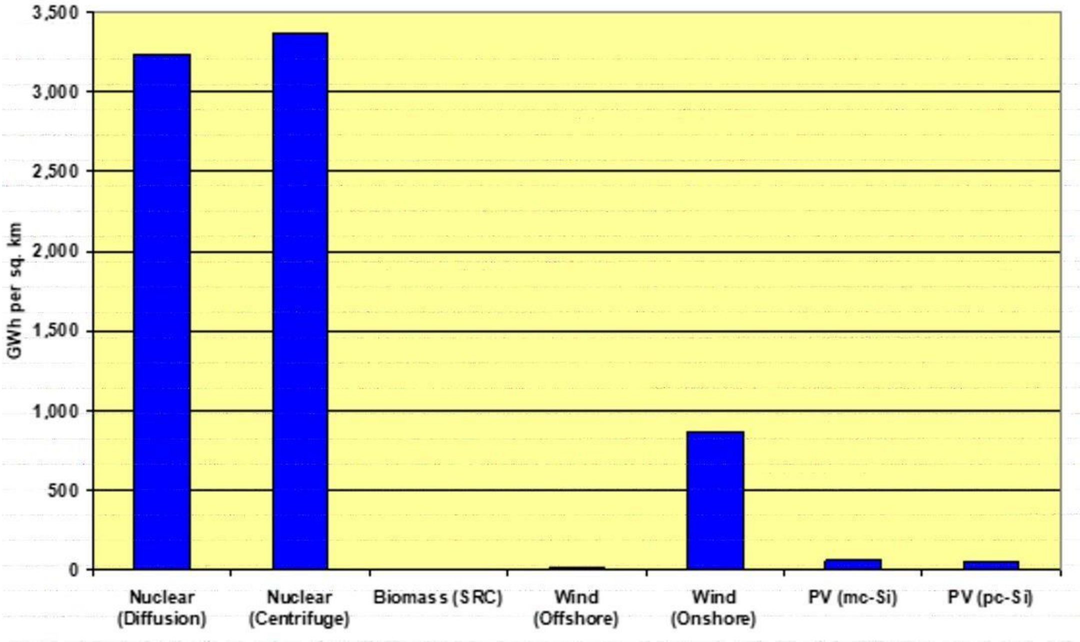

Fig. 1. Energy densities of selected power generators (GWh/km^2).
[*Source*: adapted from Cheng and Hammond, 2017.]

An examination of the *whole system* environmental burdens of the present (v2.1) *transition pathways* was undertaken by Hammond and O'Grady (2014; 2017a; 2017b) [as an extension of the earlier LCA study by Hammond *et al.* (2013) of v1.1 of the pathways]. In the initial study, the GHG emissions were the sum of both upstream and operational (or 'stack') emissions (Hammond and O'Grady, 2014). The latter emissions are those directly associated with the combustion of fossil fuels within power stations. Thus, the whole system emissions amount to those related to the 'cradle-to-gate'. The national electricity network (operated by TNOs and
DNOs) represents the downstream boundary is known as the *gate* [hence, cradle-to-gate (Hammond *et al.*, 2013)]. Both Hammond *et al.* (2013) and Hammond and O'Grady (2014) highlighted the significance of upstream emissions and their (technological and policy) implications, in contrast to the emphasis on power plant operational emissions conventionally

presented by other analysts. These upstream environmental impacts arise from the energy requirements for extraction, processing/refining, transport, and fabrication, as well as methane leakages from coal mining activities – a major contribution – and natural gas pipelines. The various life-cycle stages and processes within the system boundaries of the present study are illustrated in Fig. 3 (Hammond *et al.*, 2015; Barton *et al.*, 2018). The total *carbon dioxide equivalent* (CO_{2e}) emissions associated with various power generators and UK electricity transition pathways towards a low carbon future are depicted in Fig. 4. This illustrates the GHG trajectory under each of the three *transition pathways* in terms of per unit of electricity supplied out to 2050 (Hammond and O'Grady, 2017b). Examining the three pathways indicates that the CC pathway had significantly lower associated life-cycle emissions than its two counterparts, resulting in only 88g CO_{2e}/ kWh. The MR pathway had the highest associated GHG emissions, emitting 121g CO_{2e}/ kWh supplied, whereas the electricity supplied in the TF pathway had a GHG intensity of 107g CO_{2e}/ kWh. Nevertheless, the TF pathway almost achieved the same level of decarbonisation exhibited by the CC pathway over the total system emissions (Hammond and O'Grady, 2017b), despite having higher associated emissions per unit of electricity. There is likely to be a significant fall in carbon emissions from the UK power generation sector of some 31-51% by 2020, 65-86% by 2030, and 78-93% in 2050 (Hammond and O'Grady, 2017b). The lower figures relate to the MR pathway, whilst the higher ones are associated with the TF pathway. Notwithstanding the emphasis on GHG emissions, some of the other environmental burdens may need to be monitored (see, for example, Fig. 5).

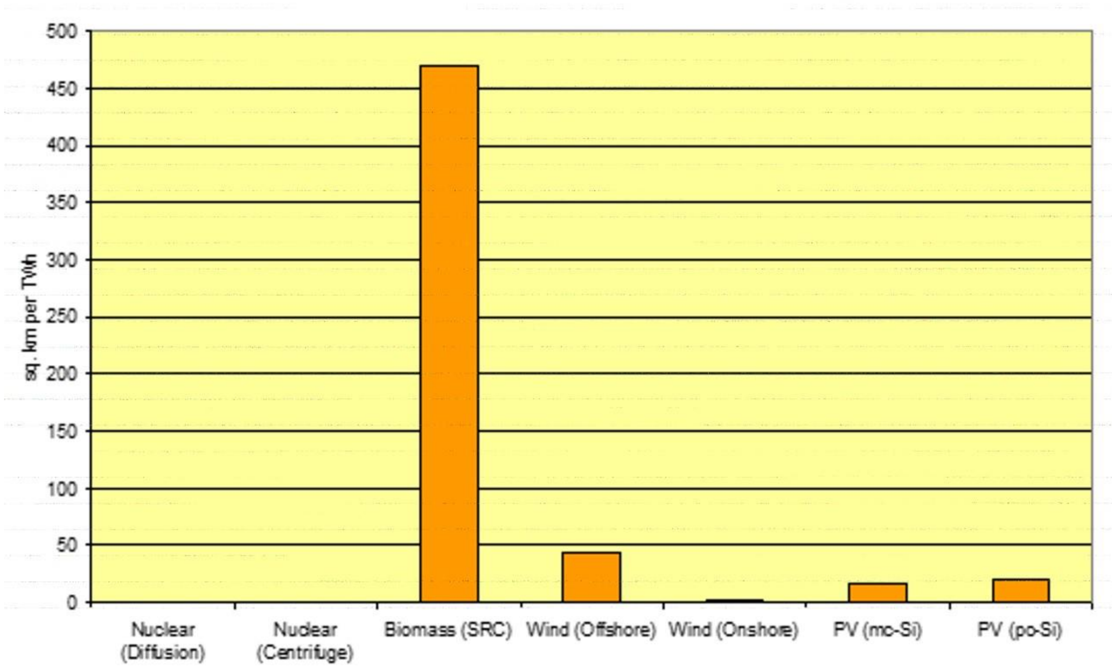

Fig. 2. Spatial footprints of selected power generators (km^2/TWh). [*Source*: adapted from Cheng and Hammond, 2017.]

The *transition pathways* LCA study by Hammond *et al.* (2013) yielded estimates of pollutants or wastes released into the environment as a consequence of the UK ESI in terms of 18 separate impact indicators (together with a tentative single score, aggregate LCA measure). The lower the resulting score for each category the better, although they do not adequately reflect, for example, the impacts associated with nuclear power generation. Nuclear is low carbon, but has a number of other health and environmental impacts associated with the potential release of ionizing radiation from nuclear power stations and processing plants. These are generally not effectively accounted for in LCA software tools (Hammond *et al.*, 2013), because they do not have an underlying basis in ecotoxicology. They studied something like 18 different impact categories, and consequently it is necessary to focus on key categories. Hammond and O'Grady (2017b) followed up this study of how the UK *phase out* of coal-fired power plants would reduce GHG emissions associated with all three v2.1 pathways. No pathway yields zero GHG emissions by 2050, due to upstream emissions (Hammond and O'Grady, 2014). This suggest that the UK electricity sector cannot realistically be decarbonised by 2030-2040 as advocated by the *Committee on Climate Change* (CCC, 2015). Significant reductions in GHG emissions are exhibited (see Fig. 4 and 5), although some environmental trade-offs that need to be monitored. Large impacts were found in terms of categories such as *Human Toxicity*, *Freshwater Eutrophication*, *Marine Ecotoxicity*, and *Natural Land Transformation* (Hammond and O'Grady, 2017b), particularly under the MR pathway (see Fig. 5). Nevertheless, *Ionising Radiation* rises modestly from the MR to CC pathways, but is obviously much lower under the TF pathway.

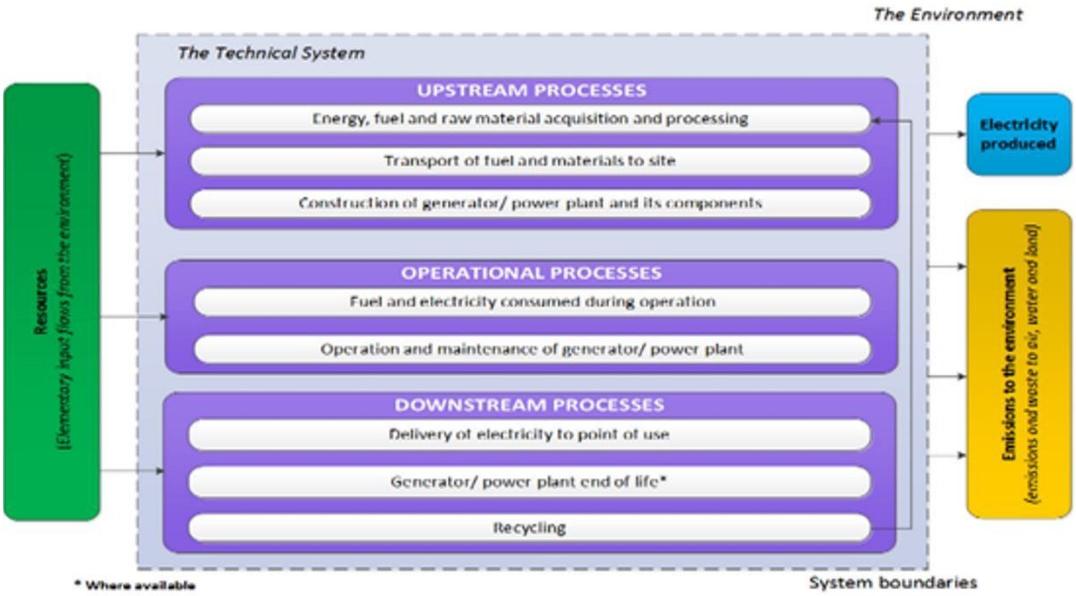

Fig. 3. System boundary diagram of the life-cycle ['cradle-to-gate'] carbon emissions assessment of the UK *Transition Pathways*. [*Source:* Barton *et al*., 2018; adapted from Hammond *et al*., 2015.]

A further LCA study assessed the way in which *natural gas* (or *methane*) is used for power generation (Hammond and O'Grady, 2017a), and the consequences of this fuel being increasingly sourced from more geographically diverse sites as conventional gas reserves diminish. These include unconventional sources, such as *shale gas* (Hammond and O'Grady, 2014) and *biomethane*. The GHG emissions associated with the three future gas supply mixes out to 2050 are presented in Fig. 6. For all three supply mixes, the associated GHG emissions increase significantly out to 2050 as a result of the incremental diffusion of new gas sources with higher upstream emissions. The central estimate GHG emission intensity of these three supply mixes ranged roughly from 13 to 16 gCO_{2e}/MJ in 2050, rising from a baseline of just under 5 gCO_{2e}/MJ in 2012 (Hammond and O'Grady, 2014). The high biogas dependence mix (Supply mix 2) had the highest associated GHG emissions, representing a 3.4 times increase in GHG emissions on the 2012 UK gas mix (see again Fig. 6). The high *shale gas* penetration mix (Supply mix 1), had the lowest central estimate of associated upstream emissions in 2050, representing a 2.7 times increase on emissions (Hammond and O'Grady, 2017a). Russian pipeline gas (Supply mix 3) had the largest uncertainty range of all the sources examined. This range was largely due to disparity in reported methane leakage rates in that region - ranging from 0.9% to 3.3 % of gas transported. For *liquefied natural gas* (LNG) and *shale gas*, the range in fugitive methane emissions were found to be a key parameter; accounting for much of the uncertainty. In contrast, the range in GHG emissions associated with *biomethane* production was primarily due to the variation in the yield from available feedstocks. Since all these supply routes played a significant role in the future gas supply scenarios examined by Hammond and O'Grady (2017a), there is a considerable uncertainty range associated with all three gas mixes.

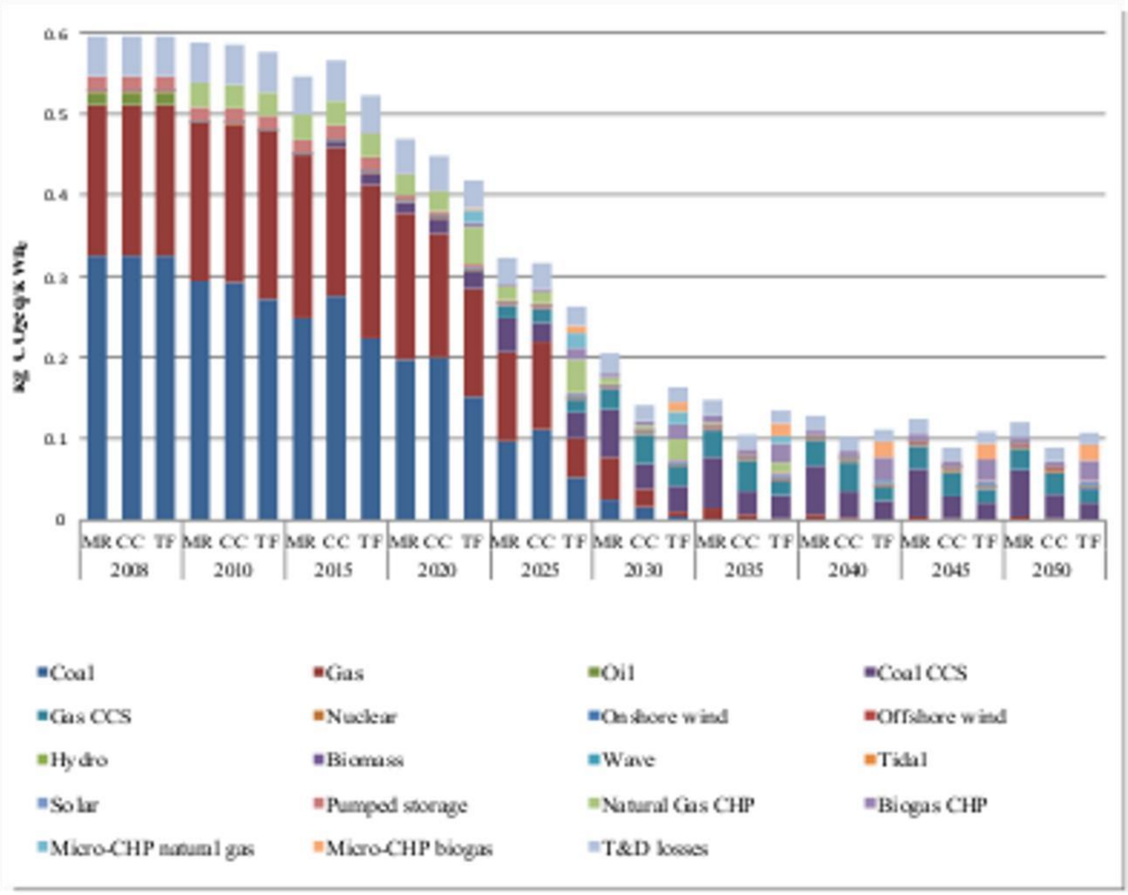

Fig. 4. Projected 'whole systems' [operational ('stack') plus upstream] GHG emissions ($kgCO_{2e}$/kWh) under all three UK *Transition Pathways*, 2008 - 2050. Environmental burdens arising from each generating technology. [*Source:* adapted from Hammond and O'Grady, 2017b.]

3.2 Environmental Footprint Analysis (EFA)

An alternative way of evaluating the environmental impacts of the three UK *transition pathways* is via carbon and environmental footprinting (Hammond *et al.*, 2019). Environmental or ecological footprints have been widely used in recent years as indicators of resource consumption and waste absorption associated transformed on the basis of biologically productive land area [in *global hectares* (gha)] required *per functional unit* (such as kWh_e). This gha is consequently a universal unit of bioproductive land area which, in the case of land types (e.g., arable or cropland) with productivity higher than the average productivity of all bioproductive land and water on the planet, the 'equivalence factor' is greater than 1. They effectively represent a partial measure of the extent to which an activity is sustainable. In order to determine the footprints associated with three UK *transition pathways*, the overall environmental footprint has been disaggregated into various components (Hammond *et al.*, 2019): bioproductive and built land, carbon emissions, embodied energy, materials and waste, transport, and water consumption (see Fig. 7). Computation of the footprint necessitates a matrix of consumption categories and land use requirements, which is ideally suited to a spreadsheet implementation. This component-based approach has enabled the sustainability challenges to be assessed quite broadly, along with specific issues (e.g., the linkages associated with the so-called energy-land-water nexus). It provides a way of evaluating the implications of a more diverse range of environmental and resources burdens than would be possible just using the LCA methodology and proprietary software.

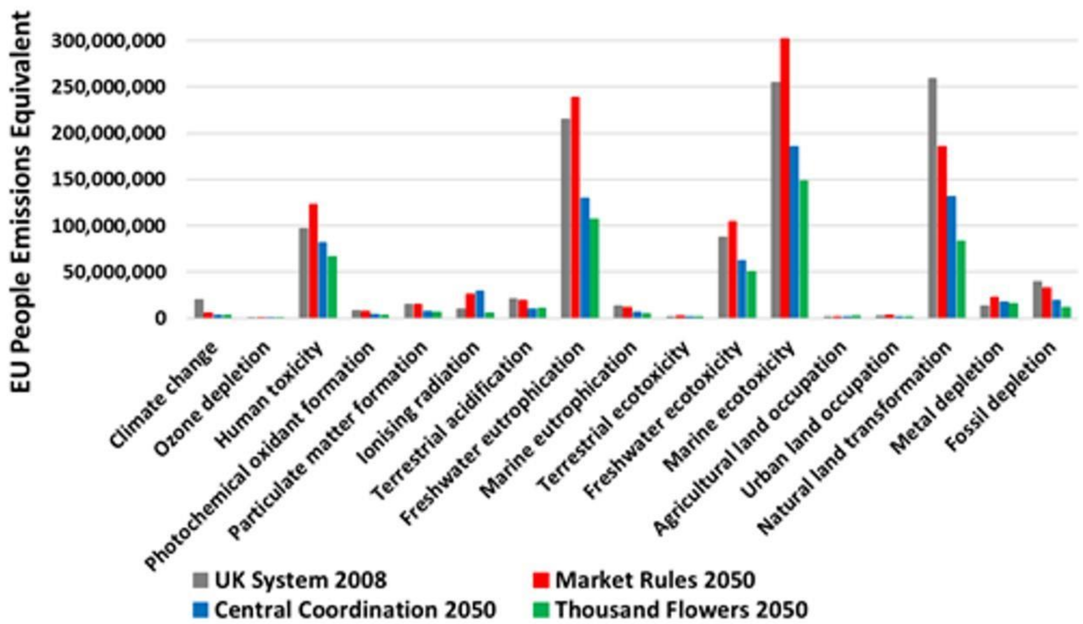

Fig. 5. 'Normalised' life-cycle environmental impacts of the electricity sector for the base year (2008) and the three UK *Transition Pathways* in 2050. [*Source:* based on data from Hammond and O'Grady, 2017b.]

Total environmental footprint for the 'baseline' year of 2010 was found to be 43 million (M) gha (Hammond *et al.*, 2019). The biggest contributor to these footprints per unit electricity (*ef*) is solid (so-called 'first generation') biofuels with 273 gha per GWh. This is due to the highest land-take of any of the technologies shown in Fig. 8 needed to grow energy crops, which is reflected in the bioproductive and built land footprint component. Carbon emissions or footprints are largely associated with fossil-fuelled power plants. The *ef* values of these plants were coal - 188 gha/GWh, oil - 141 gha/GWh, and natural gas - 95 gha/GWh respectively. Nuclear power and renewables (other than bioenergy) are near zero carbon emitters. Their *ef* values are consequently 57 gha/GWh and <25 gha/GWh respectively. The plants categorised as 'Other' represent different thermal sources that include those from various coke oven gas, blast furnace gas, waste products from chemical processes, and refuse derived fuels. It gives rise to the second largest footprint per unit electricity at 223 gha/GWh. Nevertheless, the overall *environmental footprint* (EF) of such plants is relatively insignificant, because their total power capacity is small.

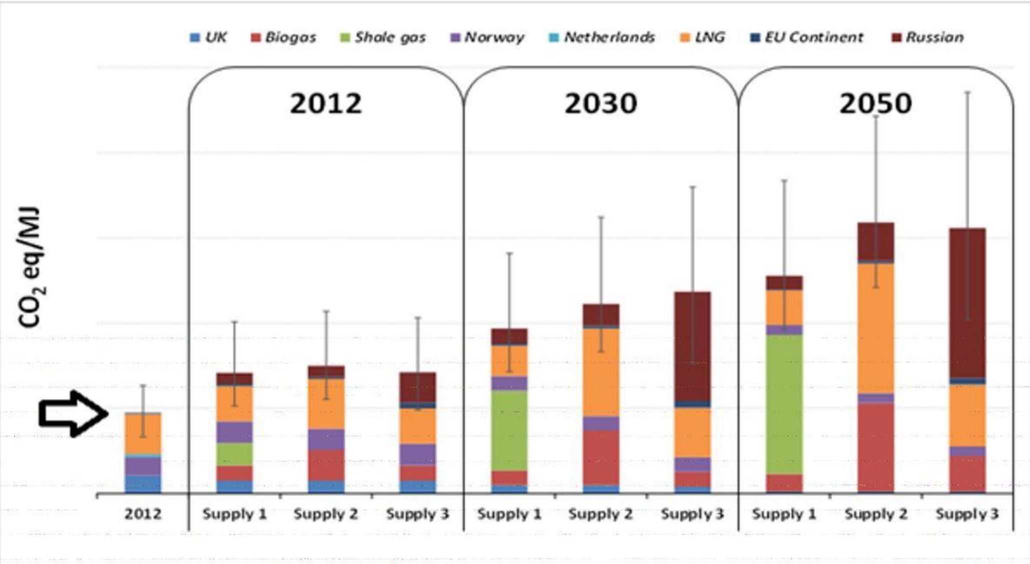

Fig. 6. GHG emissions intensity of various potential future UK gas supply mixes (per MJ of fuel delivered). Error bars represent the overall uncertainty range associated with each gas. [*Source:* based on data from Hammond and O'Grady, 2017a.]

Future carbon and environmental footprints were estimated for each of the three UK *transition pathways* (Foxon, 2013; Hammond and Pearson, 2013; Chilvers *et al.*, 2017; Barton et al., 2018). Electricity demand was projected to decrease significantly from the 2010 base year under the TF pathway by 2050 (Hammond *et al.*, 2019), but its total environmental footprint was nevertheless greater than either that under the MR or CC pathways (see Fig. 9). This is mainly due to the increase in the contribution of the bioproductive and built land component and that of the carbon footprint (rising to 10.9 and 12.5 Mgha respectively by 2050), which are both seen to be higher than in either of the MR and CC cases. The increase in these TF pathway components was mainly due to increased usage of solid biofuels for power generation (Hammond *et al.*, 2019). In order to reduce the overall TF footprint it would therefore be necessary to adopt other renewable power technologies, like offshore wind and solar PV arrays, to satisfy the increase demands caused by electrification of heat and transport. The MR and CC pathways gave rise (see again Fig. 9) to footprints of 23 and 25 Mgha respectively, as compared to 43 Mgha in the 2010 base year (Hammond *et al.*, 2019). Here the embodied energy component was the largest amongst the various footprint components; rising to 14 and 13 Mgha respectively by 2050. This was due to the large-scale use of fossil-fuelled power plants. There is a large reduction in carbon emissions under the MR pathway (over an 86% reduction compared to 2010 levels), whilst the CC pathway exhibits a slightly smaller fall (albeit nearly an 80% reduction). On the other hand, the TF pathway displays only 42% reduction in carbon emissions by 2050 (Fig. 9). Water and waste footprint components made almost negligible contributions under all three transition pathways (only ~1% footprint share), although this was recognised as probably being an artefact of the footprint methodology and assumptions adopted (Hammond *et al.*, 2019). Bioenergy and biofuel footprints and land-take (in regard to the latter, see Fig. 2 above) reflect relatively large environmental burdens when compared to other fuels.

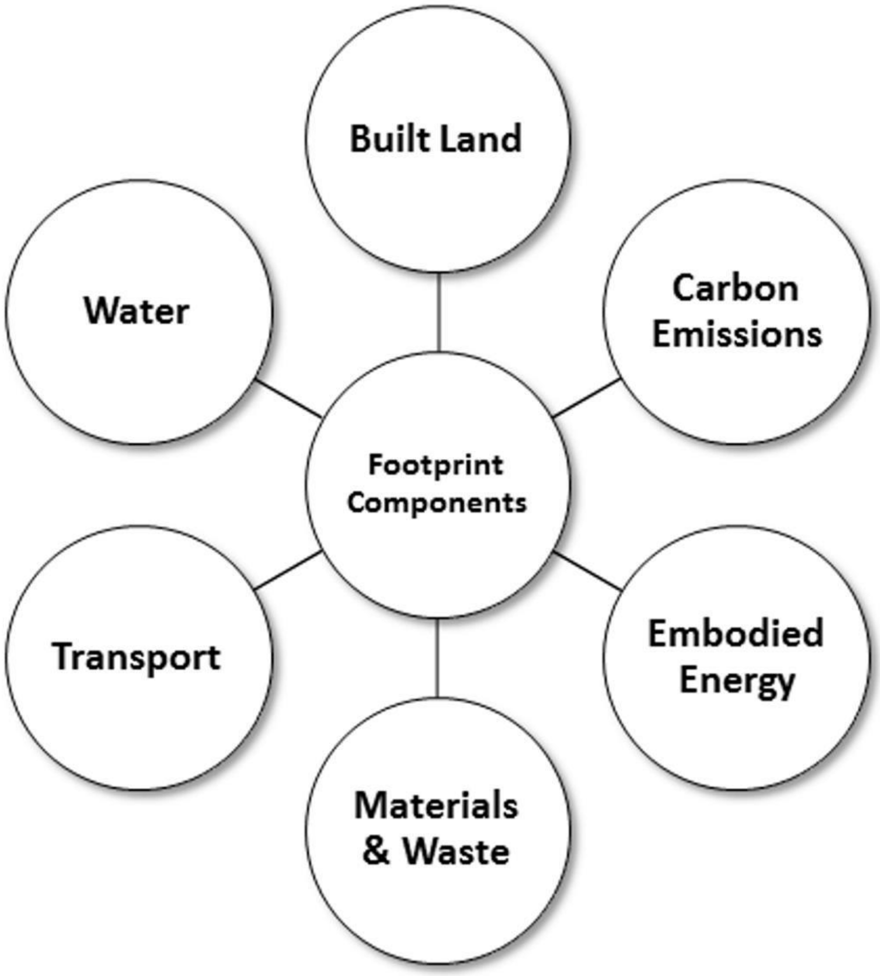

Fig. 7. Schematic representation of the component-based approach projections to environmental footprint analysis. [*Source:* Hammond *et al.* (2019); based on the method of Simmons *et al.* (2000)].

4. Concluding Remarks

A large interdisciplinary consortium of engineers, social scientists and policy analysts have developed three low carbon, more electric transition pathways for the United Kingdom (UK): described as '*Market Rules*' (MR), '*Central Co-ordination*' (CC) and '*Thousand Flowers*' (TF) respectively. The study builds on an approach based on earlier work on understanding transitions, using a multi-level perspective with landscape, regime and niche levels, and its application to the development of 'socio-technical scenarios'. These pathways to 2050 focus on the power sector, including the potential for increasing use of low-carbon electricity for heating and transport. In the companion paper (Part 1) studies of historical energy and infrastructure transitions were reported that have helped the wider understanding of the dynamics and timing of past transitions, as well as the contexts and conditions that influenced them. Pearson (2018) recently argued that historical analyses offer insights into past energy transitions that are of value to non-historians who study past, current and prospective energy transitions and, where appropriate, to policy-makers who seek to grapple with them.

The extent to which choices need to be made by UK energy policymakers and stakeholders between the large-scale and small-scale *actors*, pathways and associated technologies were again discussed in the Part 1 companion paper (see also Foxon, 2013; Hammond and Pearson, 2017). The present UK *transition pathways* highlight the fact that significantly different technological pathways to a low carbon electricity system in the UK by 2050 are possible, although any of these pathways will be challenging to realise. They imply differing levels of efforts and different patterns of risks and uncertainties and different approaches to the system's governance. Each exhibit diverse challenges in relation to energy efficiency and behavioural changes, as well as technology choices and their rate of deployment (Barton *et al.*, 2018). The way in which these are addressed and resolved will depend on the governance arrangements of the low carbon transition, including policy measures and regulatory frameworks. So the roles and choices of market, government, and civil society actors are crucial to realising any of these pathways (Chilvers *et al.*, 2017).

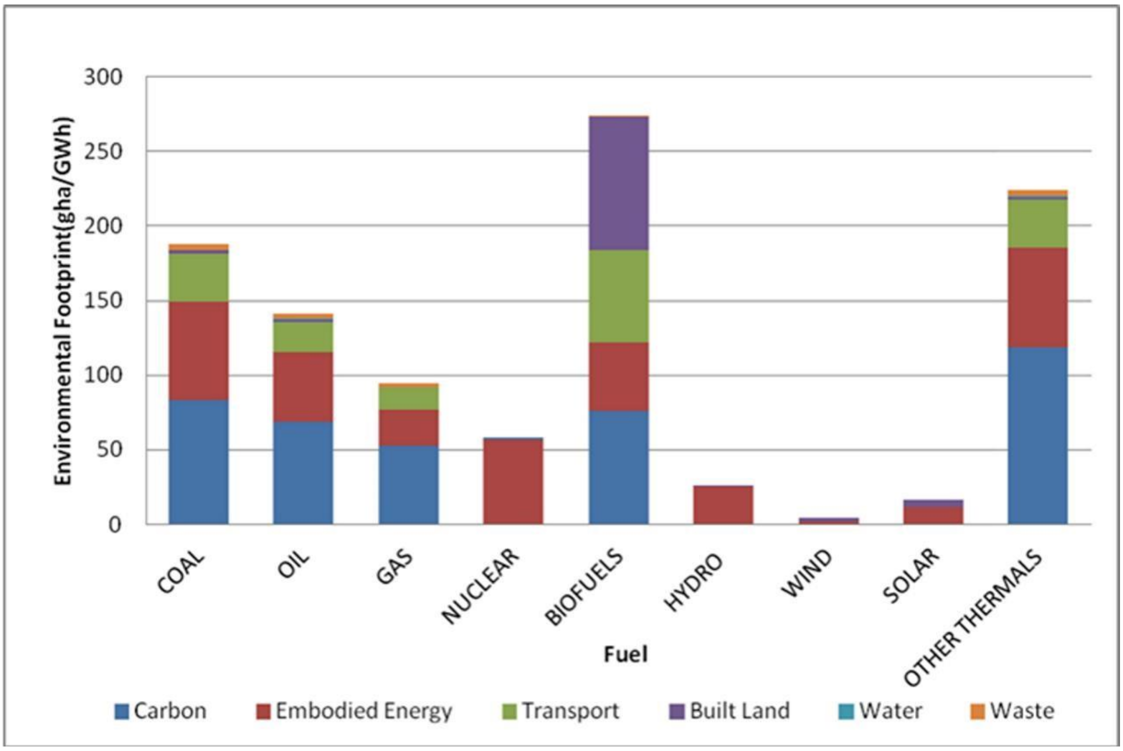

Fig. 8. Environmental footprints and associated components of power generators by fuel type in the base year of 2010. [*Source:* Hammond *et al.*, 2019.]

In the present paper (Part 2) *horizon scanning* and *energy technology assessments* (ETAs) have been conducted on the energy technologies that influence the three UK *transition pathways* provides an understanding the future interplay of the energy policy *trilemma*, i.e., achieving deep GHG emission cuts, whilst maintaining a secure and affordable energy system, and addressing how resulting tensions might be resolved. Indicative ETAs were used to evaluate a number of potentially disruptive energy technologies (Chilvers *et al.*, 2017): UK *shale gas* extraction, *carbon capture and storage* (CCS), nuclear power plants, and tidal power barrages, as well as other potentially 'green' energy options (ARBTs and REEs as a constraint on *clean* energy technologies). These studies have sought to identify the components of a *balance sheet* of technological credits and debits in order to evaluate their societal impacts, and to determine whether they are compatible with Britain's move towards a low carbon future in 2050 and beyond.

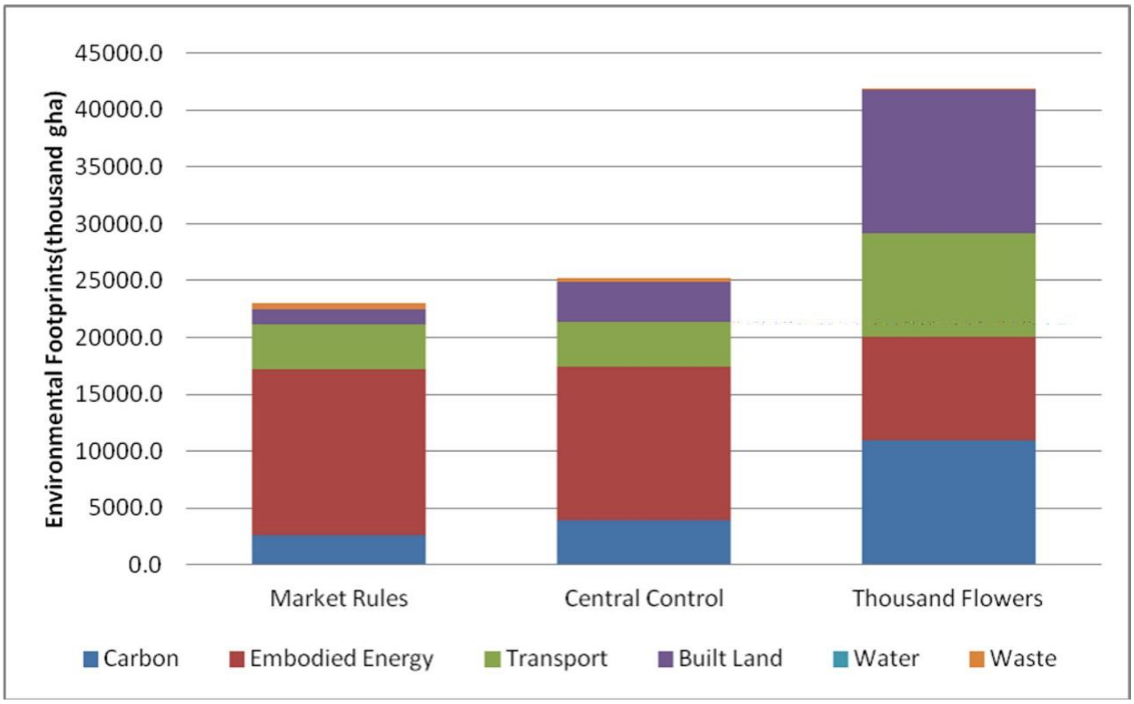

Fig. 9. The environmental footprint and associated components of the UK electricity sector in 2050 under all three UK *Transition Pathways*. [*Source:* Hammond *et al.*, 2019.]

All three pathways have been evaluated here (in this Part 2 of the paper) in terms of their environmental performance using complementary life-cycle assessment and footprinting methods. A critical state-of-the-art review of this environmental *life-cycle assessment* (LCA) methodology has identified its current strengths and weaknesses for energy practitioners and policy analysts (Hammond *et al.*, 2015). The extraction and delivery of fuel requires energy and creates GHG emissions. The upstream emissions associated with various power generators and UK electricity *transition pathways* have been evaluated on a *whole systems* basis (Hammond and O'Grady, 2014). There will remain further emissions upstream that are unaccounted for, because neither the relevant UK Government department nor their independent advisors [the *Committee on Climate Change* (CCC, 2015)] generally account for upstream fugitive GHG emissions beyond UK borders - even if the current UK GHG reduction targets are apparently met. Large impacts were also found in terms of categories such as *Human*

Toxicity, *Freshwater Eutrophication*, *Marine Ecotoxicity*, and *Natural Land Transformation* (Hammond and O'Grady, 2017b), particularly under the MR pathway. Finally, the carbon footprints and EFs of the three UK *transition pathways* have also been evaluated. Here the overall environmental footprints were disaggregated into: built land, carbon emissions, embodied energy, materials and waste, transport, and water consumption. This componentbased approach has enabled the sustainability challenges to be assessed quite broadly, along with specific issues (e.g., the linkages associated with the so-called energy-land-water nexus).

So-called 'disruptive' technological options have therefore been examined (again in Part 2 of the contribution) in order to provide recommendations on the framing of future energy policy choices that limit the environmental consequences of future electricity systems. It is argued that the value of any new policy direction must be evaluated not only against medium-term climate change (or GHG emission) goals, but against long-term, system-wide goals over a wider spectrum of environmental metrics. Lessons can clearly be drawn from this *transition pathways* project for other industrialised nations attempting to decarbonise their electricity generation systems, although local circumstances will determine the country-and regionspecific options.

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